Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24 July 2008, Zurich, Switzerland

Effectiveness of strengthening RC beam-column connections in shear with vertical FRP strips

R. Shrestha[1], S.T. Smith[2] & B. Samali[1]
[1] *Centre for Built Infrastructure Research, University of Technology Sydney, NSW, Australia*
[2] *Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China*

ABSTRACT: Reinforced concrete (RC) connections, designed prior to the implementation of earthquake design standards around the world, may not posses sufficient shear strength to withstand a seismic attack. Such connections will therefore require strengthening. This paper reports the results of tests on two-dimensional RC connections which have been strengthened in shear with externally bonded fiber reinforced polymer (FRP) composite strips. FRP strips are an attractive strengthening solution as they are relatively simple to apply, and in this study they are orientated parallel to the longitudinal axis of the column (i.e. vertical strips). The tests reported in this paper serve to evaluate the effectiveness of the use of vertical FRP strips for strengthening and as a result, the test specimens are heavily instrumented in order to monitor not just the FRP but the connection as a whole. The hierarchy of strength dictates eventual failure in the joint region, even for the FRP strengthened connections, and all test specimens are subjected to monotonic or cyclic loading.

1 INTRODUCTION

Reinforced concrete (RC) structures, which were gravity load designed prior to the implementation of earthquake design standards, may not posses sufficient shear strength in the joint region of the connections where the beam/s frames into the column. The shear strength of such a joint (herein referred to as *connection*) may not be sufficient to withstand the large shear forces induced during a seismic attack and may therefore not lead to the desired formation of a strong column-weak beam mechanism in the structure due to premature joint failure. Therefore, there is a need not only to strengthen existing connections in shear but to also increase the energy absorption capacity to ensure desirable performance under seismic attack. The use of externally bonded fiber-reinforced polymer (FRP) composites to strengthen shear deficient connections has been proven to be effective from past studies. Both two-dimensional external (i.e. one beam framing into a column) and internal (i.e. two beams framing into a column) connections have been strengthened in shear with externally bonded FRP. A comprehensive review of experimental research to date in addition to an evaluation of the effectiveness of the strengthening schemes is given in Smith and Shrestha (2006). Most strengthening schemes utilised FRP sheets which covered a large portion of the joint region thus making it difficult to assess the behavior of the concrete in the joint region. The test connections were also subjected to cyclic loading thus making it difficult to monitor the behavior of the FRP and report the failure mode in detail.

This paper reports the results of tests on RC connections strengthened in shear with externally bonded FRP strips orientated parallel to the longitudinal axis of the column. The strengthening scheme was chosen specifically upon consideration of the ease and viability in practical application. Also, FRP strips were chosen over sheets in order to more easily observe the progression of cracking in the joint region in addition to detecting the occurrence of FRP debonding. The primary objectives of the tests were to observe the behavior of the FRP strengthening and accurately report the failure mode. Linear variable displacement transducers (LVDTs) and strain gauges were extensively used. Connections were subjected to both cyclic as well as monotonic loading with the motivation of monotonic loading being to accurately monitor the behavior of the FRP strips and development of cracking in the joint region and the cyclic loading to observe the energy absorption capacity of the strengthened connection.

2 EXPERIMENTAL DETAILS

2.1 *Description of Test Specimens*

Two sets of external connections, two in each set, were tested (Table 1). All connections possessed no transverse reinforcement in the joint region, thus representing shear deficient connections. All connections had identical geometric and reinforcement details (Figure 1). The hierarchy of strength design of all the connection dictated shear failure in the joint region (with and without joint strengthening) followed by beam flexural failure then column flexural failure.

The first set of connections was tested under monotonically increasing load and the second set was tested under cyclic load. One connection in each set (UM1 and UC1) was an unstrengthened control connection while the others (SM1 and SC1) were strengthened. Carbon FRP (CFRP) was used for all strengthening. The FRP strengthening scheme (Figure 1d) consisted of two layers of 50 mm wide strips of FRP, spaced at 150 mm centers, applied centrally on both sides of the joint face and extended into the column. Two layered column wraps were provided to both ends of the strip for anchorage against global debonding of the vertical strips.

Table 1. Summary of test connections

Connection #	UM1	SM1	UC1	SC1
Description of test	Control	FRP-strengthened	Control	FRP-strengthened
Load Type	Monotonic	Monotonic	Cyclic	Cyclic

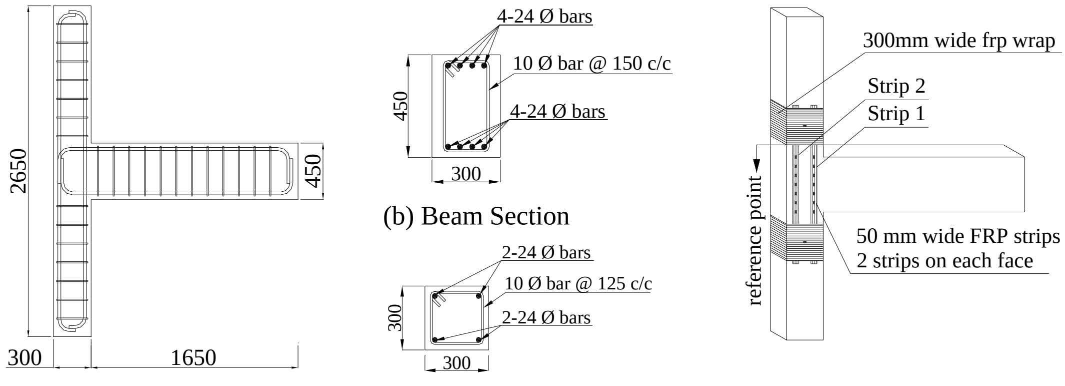
U = unstrengthened (control), S = strengthened, M = monotonic loading and C = cyclic loading

2.2 *Material properties*

Concrete cylinder compressive strength tests on the day of each connection test (compressive tests on three 150mm diameter cylinders per connection) are summarised in Table 2 while the yield strengths of the longitudinal and transverse reinforcement were 532 MPa and 332 MPa respectively (tensile test on 3 test coupons). The tensile strength and rupture strain of the CFRP were 3120 MPa and 1.1% respectively (tensile tests on two-layered 5-15mm wide coupons with 0.117 mm nominally thick carbon fibre sheets).

2.3 *Test Set-up, Instrumentation and Experimental Procedure*

The test set-up is shown in Figure 2. The connection was mounted on a stiff test rig with hinge supports at both ends of the column (i.e. column orientated horizontal to the ground) while load was applied to the beam tip through an actuator mounted on a stiff reaction frame. An axial load of 180 kN (equal to 8% of the gross axial load capacity of the column and representative of a typical floor loading) was applied to the column using a hydraulic jack attached to one end of the column and through a system of high strength bars. For the first set of connections (UM1 and SM1), tested under monotonically increasing load, load was applied in increments of 10 kN steps and cracks were marked at every load step until no new cracks were observed. For the second set of connections (UC1 and SC1), load was applied to the beam tip in increasing steps of 5 mm deflection in each cycle in each push-pull direction. The deflection step was increased to 10 mm after the 8th cycle for FRP strengthened connection SC1 due to no significant change in the load. Cracks were marked on the test specimen at the peak deflection in each push and pull cycle until no new cracks were observed. The load was applied using a deflection controlled mode in all tests at a loading rate of 0.2 mm per second.



(a) Geometry (c) Column Section (d) FRP strengthening

Figure 1. Test connection – geometric and reinforcement details and strengthening scheme

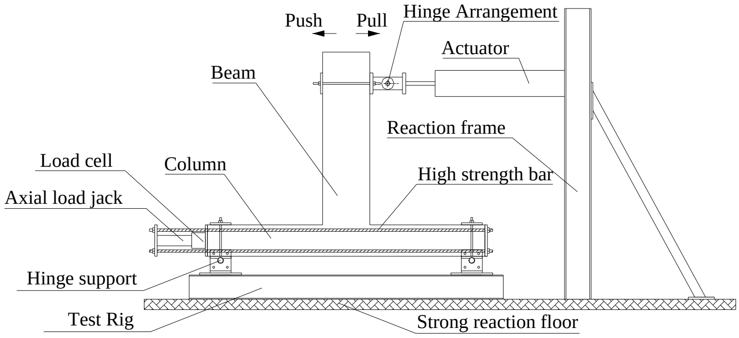


Figure 2. Test setup

Twelve LVDTs were used, three to measure deflection along the length of the beam while the rest were used for monitoring key locations such as the supports and other critical region of the test rig. External gauges on the concrete and internal gauges on the reinforcement bars were also used for strain measurement; location diagrams of these instruments have however not been shown. In the FRP strengthened connections, SM1 and SC1, additional gauges were applied on the FRP surfaces. Seven strain gauges were attached on each FRP strip on the front face and 3 gauges each on the back face of each connection as shown in Figure 1d (for the front face). Only these FRP strain gauge readings will however be reported in this paper.

3 EXPERIMENTAL RESULTS

3.1 *Cracking Behaviour and Failure Mode*

The final crack patterns of all tested connections in the joint region are shown in Figure 3.

3.1.1 *Control connection UM1 – monotonic loading*

The connection failed by shear failure in the joint. Minor flexural cracks were observed in the beam followed by cracks at the beam-column corner in the early stage of the test. A major diagonal shear crack was observed in the joint region at a load of 70 kN (13.2 mm deflection). At a peak load of 96.4 kN (27.7 mm), the connection lost its load carrying capacity owing to severe shear cracking in the joint region. The test was stopped shortly after the peak load was reached. The connection was then repaired and retested however these results are not presented in this paper. The final crack pattern is shown in Figure 3a.

3.1.2 *FRP strengthened connection SM1 – monotonic loading*

Some minor flexural cracks were observed in the beam followed by cracks at the beam-column corner as the connection was loaded to 10 kN. A diagonal crack in the joint region was observed as the load was increased from 70 kN to 80 kN (19 mm deflection) and cracking noise was heard indicating localised debonding of FRP and cracking of the epoxy resin. The peak load of

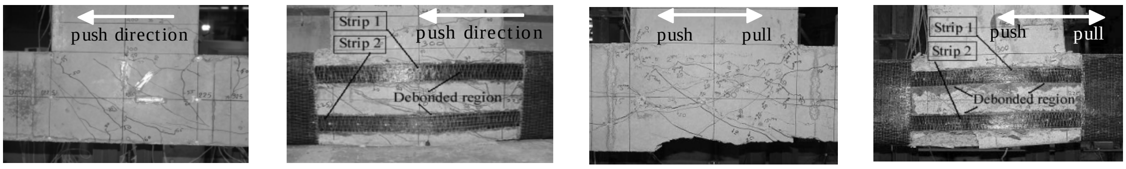
103 kN was achieved at a deflection of 32 mm when FRP strip 1 (refer to Figure 1d and Figure 3b for strip location) debonded along its whole length followed by a loss of load carrying capacity of the connection. The connection ultimately failed by joint shear failure. The column wraps which secured the ends of the FRP strips prevented the strips from completely debonding however the effectiveness of the FRP was lost upon local debonding. Strip 2 debonded after the peak load was reached. The exact debonded region of FRP was difficult to determine from visual inspection however the FRP strain gauge results reported in Section 3.3 help shed some light the location of debonding. The final crack pattern in the joint region is shown in Figure 3b.

3.1.3 *Control connection UC1 – cyclic loading*

Diagonal shear cracks in the joint region and flexural cracks in the beam formed as the first load cycles were applied. Subsequent load cycles resulted in formation of diagonal shear cracks with increased opening. A peak load of 83.2 kN (at 29.8 mm deflection in 6^{th} cycle) in the push direction was observed. The connection failed by joint shear failure and the final crack pattern in the joint region is shown in Figure 3c.

3.1.4 *FRP strengthened connection SC1- cyclic loading*

Unlike the control connection, only minor diagonal cracks in the joint region and flexural cracks in the beam were observed in the first cycle. Only in the second cycle did a major diagonal shear crack start to appear and first FRP debonding observed (at 72 kN load and 8.25 mm deflection in push direction). The FRP strengthening was effective in limiting the severity of cracking in the joint region and the strength degradation in subsequent load cycles was more gradual compared to the control connection UC1. A peak load of 97.8 kN (at 24.4 mm deflection in 5^{th} cycle) in the push direction was observed when FRP strip 1 debonded (refer to Figures 1d and 3d for strip 1 location). Ultimate failure was due to major diagonal joint shear cracking following local debonding of the FRP strips. The column wraps at the ends of the FRP strips prevented the strips from completely debonding however the effectiveness of the FRP was lost following localised debonding. Figure 3d shows the final crack pattern in the joint.

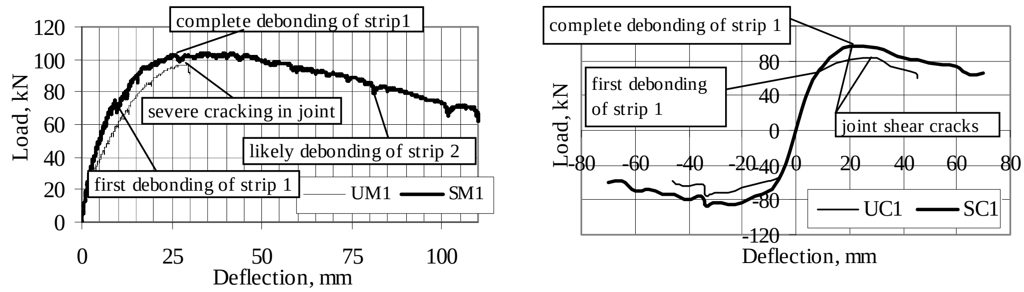


(a) UM1 (monotonic load) | (b) SM1 (monotonic load) | (c) UC1 (cyclic load) | (d) SC1 (cyclic load)

Figure 3. Final crack patterns for tested connections

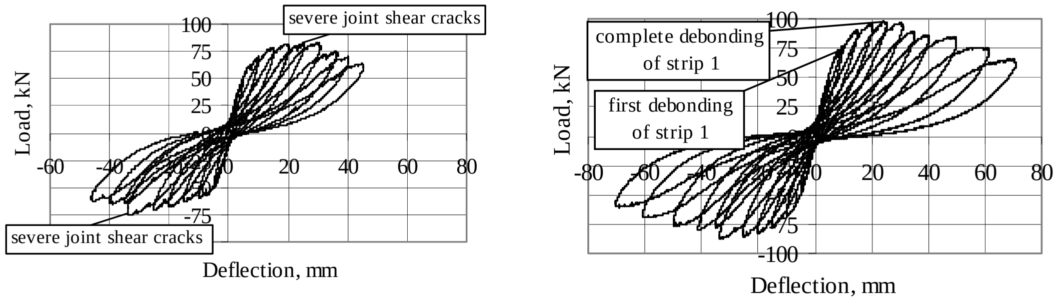
3.2 *Effectiveness of FRP strengthening*

Load-deflection responses for monotonic and cyclic load tested connections are shown in Figures 4 and 5 respectively and the peak load for all connections are summarised in Table 2. Load capacities of monotonic load tested connections were higher than their cyclically loaded counterparts due to strength deterioration resulting from load reversal for the latter. The FRP strengthening was particularly effective in the cyclic load tests where the FRP resulted in enhancement of the load carrying capacity of the connection by about 17%. Comparison of peak-to-peak stiffness (Figure 6a) shows stiffness degradation to be more gradual in the FRP strengthened connection and the connection still had significant stiffness at a high deflection level. The FRP strengthened connection also showed better energy dissipation capacity compared to the control at higher deflection level (Figure 6b). The FRP strengthening was also effective in limiting the severity of the joint shear cracks based on visual inspection. Comparison of the peak load-deflection envelop for the control and FRP strengthened connection is shown in Figure 5a. In case of connections tested under monotonic load, FRP strengthening resulted in a slight enhancement of the load carrying capacity in addition to the increase in stiffness. The FRP strengthening was more effective in the cyclic tests as the strengthening was effective in limiting the shear cracks in the joint which is critical in strength deterioration in cyclic loading.



(a) (b)

Figure 4. (a) Load-deflection plot - (b) Load deflection envelop - cyclic load tests

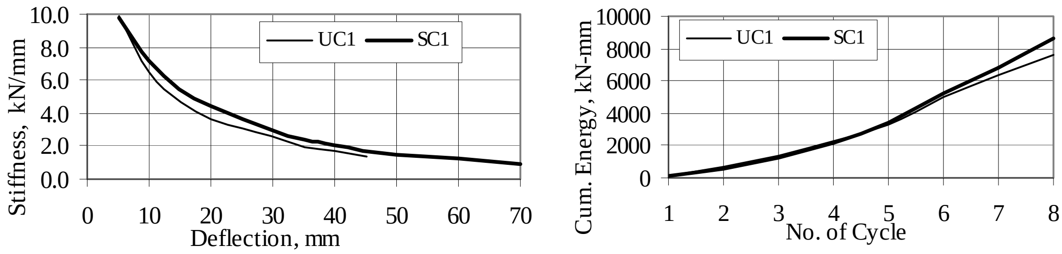


(a) Control Specimen: UC1 (b) Strengthened Specimen: SC1

Figure 5. Load versus beam-tip deflection response

Table 2. Summary of load and deflection for all connections

Connection	f'$_c$ (MPa)	Peak Load (kN)		Deflection at Peak Load (mm)		Increment (kN)		Increment (%)	
		Push	Pull	Push	Pull	Push	Pull	Push	Pull
UM1	25.4	96.4		26.7					
SM1	25.6	103.0		32.0		6.6		6.8	
UC1	25.6	83.2	75	29.8	33.5	-	-	-	-
SC1	25.8	97.8	87.5	24.4	33.4	14.6	12.5	17.5	16.6

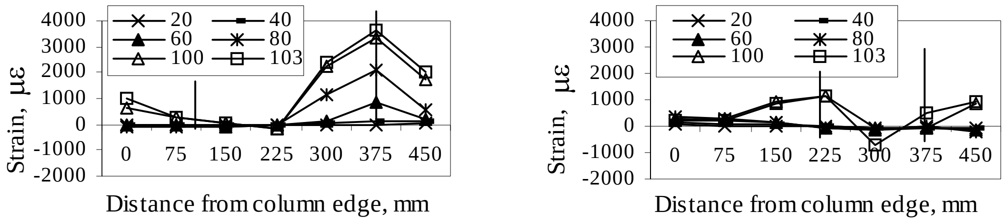


(a) (b)

Figure 6. Comparison of result (a) peak-to-peak stiffness (b) cumulative energy dissipated

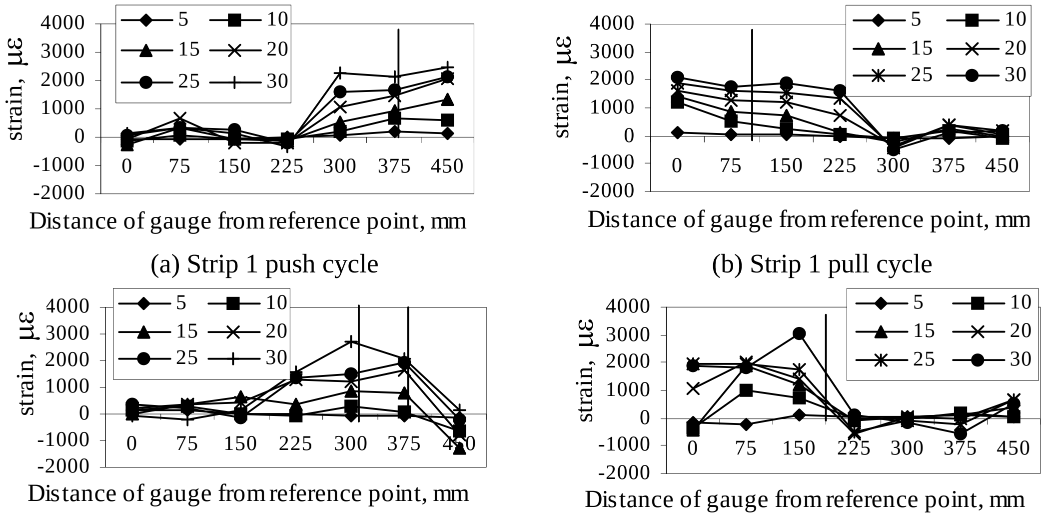
3.3 *FRP Strain Results*

Strain distributions for strip 1 and 2 (refer to Figure 1d for locations) for the monotonically loaded strengthened connection (SM1) at different load levels (up to peak load) are shown in Figure 7. The strain distribution for strips 1 and 2 for the cyclically loaded strengthened connection (SC1) at different beam tip deflection levels (up to peak load) is shown in Figure 8 for both push and pull directions. The positions where shear cracks intersected the FRP strips are represented as vertical lines in Figures 7 and 8. High strain was recorded on the FRP adjacent to the intersection of the FRP with the joint shear cracks; adjacent low strain signifying no debonding or compressed regions. The peak strains observed in the strips in both FRP strengthened connections were much lower than the FRP rupture strain (rupture strain = 11000 $\mu\varepsilon$). However, it should be noted that as the strain gauges were not located exactly where the shear crack intersected the FRP strips (i.e. the position of the shear cracks were not known in advance of the placement of the strain gauges), the plots may not represent the actual peak strain values. For the monotonic load test result in Figure 7a, only a portion of FRP strip 1 appears to have debonded, unlike the visual observation in which the whole strip was observed to debond. Note the constant strain readings along approximately half the length of strip 1 for the pull cycle, as well as the push cycle, for connection SC1 (Figure 8b) signifying virtually complete debonding of the strip. Also note the difference in distribution of strain in FRP strips of connection SM1 tested under monotonic loading. Relatively higher strain values were observed in strip 1 compared to strip 2 indicating that strip 1 was the main shear resisting strip. However, such a difference in strain results for cyclic load test was not observed which may be due to more cracks opening in the joint region under cyclic loading.



(a) Strip 1 (b) Strip 2

Figure 7. Distribution of strain along length of each FRP strip for connection SM1 – monotonic load



(a) Strip 1 push cycle (b) Strip 1 pull cycle

(c) Strip 2 push cycle (d) Strip 2 pull cycle

Figure 8. Distribution of strain along length of each FRP strip for connection SC1 – cyclic load

4 CONCLUSIONS

The effectiveness of vertical FRP strips for the strengthening exterior connections in shear was investigated. FRP strengthening was effective in preventing extensive cracking in the joint region compared to plain RC connections, especially for the cyclically loaded specimens, however the capacity of the strengthened connection was limited by premature localised debonding of the FRP. Debonding of the FRP must be prevented or delayed in enhance its effectiveness.

5 ACKNOWLEDGEMENTS

This project was funded by Australian Research Council (ARC) Discovery Grant DP0559567. The financial assistance of the ARC is gratefully acknowledged.

6 REFERENCES

Smith, S.T. and Shrestha, R. (2006) “A review of FRP-strengthened RC beam-column connections”, *Proceedings, Third International Conference on Composites in Civil* Engineering, *CICE 2006*, Eds. A. Mirmiran and A. Nanni, 13-15 December, Miami, USA, pp. 661-664.